

# **Research at NCAR on the Topics of Data Assimilation Singular Vector Analysis, and Some General Adjoint Applications**

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## **LONG-TERM GOALS**

This proposal covers some broad topics that are of mutual interest to scientists at NCAR and NRL Monterey. The research topics include aspects of data assimilation, singular vector analysis, and more general adjoint model development and applications. The work is being coordinated with NRL staff so as to augment, rather than duplicate, what is being done by them. The emphasis at NCAR will be on fundamental aspects of the problems, including, but not limited to: characterization of error statistics and implications of non-normal distributions, development of appropriate mesoscale balance conditions, development of norms that measure moisture for defining singular vectors, and parameterization of model Jacobians for efficient and effective tangent linear and adjoint calculations. Much of what is done is instructional. The support provided by ONR augments work being performed at NCAR and allows continuation of extensive collaborations between the P.I. and NRL staff.

## **OBJECTIVES**

The new science this year was concerned with 3 different scientific problems: (1) estimation of analysis error statistics through examination of differences between products produced at different centers; (2) development of an appropriate initial perturbation technique for ensemble forecasting; and (3) examination of singular vectors (SVs) for moisture-measuring norms.

## **APPROACH**

The ECMWF and NCEP reanalysis are obtained on pressure surfaces. Some horizontal interpolations and spectral filtering are required to get them on the same grid so that consistent differences can be taken. Statistics of these differences are then analyzed for single winter and summer seasons. Some of these are expressed in terms of power spectra of spherical harmonic coefficients.

The perturbation technique developed for NRL is based on Errico and Baumhefner (1987). The initial perturbations are produced randomly, consistent with estimates of local analysis error variance produced by NAVDAS and consistent with assumptions made about shapes of vertical and horizontal correlations of analysis error.

The tool for producing singular vectors is NCAR's Mesoscale Adjoint Modeling System (MAMS2, Errico and Raeder 1999). This is a limited area, meso- $\alpha$  scale, primitive equation model that includes

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a complete physics package except for above-surface radiation effects. It also includes a vertical mode initialization package. It is the only model with complete (not simplified) moist physics that has corresponding tangent linear and adjoint versions with demonstrated utility (Errico and Raeder, 1999).

## **WORK COMPLETED**

Investigation of the difference between the ECMWF and NCEP analysis has been completed for 2 seasons. This includes determination of means, standard deviations, horizontal spectra, and vertical correlations as well as display of the results in a variety of forms. A manuscript is being prepared by Steve Mullen at the University of Arizona and graphical presentations have been prepared by Kevin Raeder at NCAR.

The new perturbation software based on Errico and Baumhefner (1987) has been developed. It has been interfaced with the NOGAPS and NAVDAS systems at NRL. It has been tuned to be consistent with results from the aforementioned study of reanalysis differences. This work was completed with the collaboration of Tom Rosmond and Carolyn Reynolds at NRL.

A paper summarizing what is now known about synoptic-scale atmospheric predictability has been prepared with the collaboration of David Baumhefner at NCAR for publication in the Bulletin of the AMS. It includes a detailed synoptic description of one case as well as a summary of results over a season. Descriptions are in terms of synoptic maps, horizontal spectra, and statistics, including those of perturbation ensembles.

An investigation of singular vectors determined using moisture-measuring norms has been completed. Four very different synoptic cases were examined in order to obtain a range of behaviors. Norms included inverse variance weighted measures of moisture as well as more standard versions of the energy norm at the initial time. At the final time (forecast hour 12), both the standard energy norm and one determined as the mean squared perturbed precipitation were considered. Attention was restricted to the leading 4 SVs for each experiment. The meaningfulness of the SV results in realistic corresponding nonlinear calculations was confirmed. A manuscript has been prepared for submission and is currently under preliminary internal review. This work has been performed with the assistance of Kevin Raeder at NCAR and the collaboration of Martin Ehrendorfer at the University of Innsbruck, Austria.

## **RESULTS**

Taken as a proxy for analysis error, the analysis differences reveal significant longitudinal as well as latitudinal dependence of analysis error variance. The spectrum of spherical harmonic coefficients of the differences at each pressure level is rather flat. Unfortunately, since the archived NCEP re-analysis data are truncated at T36 resolution, the crossover of the analysis and difference spectra, indicating where the small scale "noise" is as great as the signal, could not be determined for most fields. Vertical correlations of the differences may be approximated by a Gaussian in log-pressure coordinates, with a scaling such that correlations with a value at 500 hPa drop to 0.5 in within 150 hPa.

The initial ensemble perturber produces analysis differences that resemble the differences seen between the re-analysis products. In particular, their horizontal spectra are rather flat except at small scales and the vertical correlations, as constructed, look like those of the re-analysis differences in the

mean. Their variances, although constructed from NAVDAS, resemble those of the analysis differences also.

Errors due to uncertainty of initial conditions typically double every 1.5 days for the first few days of a forecast, when such averages are computed hemispherically. Otherwise, the growth is local, being associated with certain small-scale baroclinic waves. Typically, by day 8 of a forecast, its uncertainty is so large that it has very little utility. Error growth occurs primarily at the scale of developing baroclinic waves at two-dimensional wavenumbers 10-20. Sometimes growth associated with one feature is abated in time; other times, new areas of growth occur. The latter results suggest that confining initial perturbations to only regions of past growth or current growth, as done for ensembles based on bred growing modes or singular vectors, is disadvantageous.

Examination of the SVs produced for moisture measuring norms yielded some interesting results. It confirmed results, from an earlier study using an adjoint model, that reasonable moisture perturbations can have as great an impact on measures such as dry perturbation energy (and winds) as initial perturbations of dry fields (in particular, temperature) alone. In a few cases, it showed that initial moisture and temperature perturbations could independently produce the same perturbation in a 12 hour forecast. This result depends on the heating generated by non-convective precipitation. Also in some cases, the optimal perturbation that maximized perturbation energy was nearly the same as the one that maximized perturbation precipitation, although this was not true in most cases.

## **IMPACTS/APPLICATIONS**

The main application of our determination of statistics of analysis differences is for use as a proxy of analysis error statistics, especially for tuning of an initial perturbation generator for producing ensemble forecasts. This is the only estimate of covariance statistics that arguably resemble analysis error statistics produced by modern data assimilation systems.

The new initial perturbation generator is the prime candidate for use in a new ensemble forecast system being developed by NRL for implementation at FNMOC. Unlike perturbation techniques developed elsewhere, this will be the only scheme for which it can be reasonably claimed that the perturbation statistics resemble those of analysis uncertainty. Importantly, the new scheme does not impose presuppositions of where future error growth may occur.

The study of SVs for moisture measuring norms reveals a potentially strong effect on forecast error due to initial moisture uncertainty. As such, the importance of (1) improving moisture analysis, (2) including moist processes in SV and adjoint model studies, and (3) including moisture in initial perturbation techniques is highlighted. The results call for greater and wider development of moist adjoint models and their applications.

## **TRANSITIONS**

The ensemble initial perturbation software has been ported to NRL and is now being investigated by researchers there as the prime candidate for a new ensemble forecast system being developed for FNMOC. The tuning of this new technique is based on results produced for the three other studies described.

## RELATED PROJECTS

Determination of mesoscale predictability limits with respect to uncertainty in the larger-scale environment, that is a project funded by ONR with Joseph Tribbia and David Baumhefner (NCAR) as CO-PIs.

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